17th International Conference
ENGINEERING MECHANICS 2011
Svratka, Czech Republic, 9 – 12 May 2011

CFD SIMULATION OF FLOW OVER A WAVY SURFACE

S. Knotek*, M. Jícha*

Abstract: *The paper presents CFD simulation of flow over a wavy surface for selected geometric configurations and external flow velocities. The simulation characteristics and results are described in relation to the computational model whose assumptions are confirmed. The wall shear stress and pressure profile are investigated in dependence on the ratio of the wave amplitude to the wavelength.*

Keywords: ***CFD, wavy surface.***

1. Introduction

The motivation of the general problem of gas flow over solid wavy surface can be seen in the efforts to propose computational models for prediction of hydrodynamic instabilities, which are generated by air flowing over the liquid film surface. Among a variety of approaches, the so-called quasi-static approach has its importance. It is based on the assumption that, for large ratios of fluid viscosities, the surface can be considered as static and solid. In the first step, the force effects of the gas flow acting on the solid surface defined by amplitude and wavelength are evaluated. These forces are then included in the calculations of the main problem of instability prediction.

As a crucial physical quantity for the instability occurrence, the shear and pressure forces acting on the wavy liquid surface have been identified (Hanratty, 1983). To calculate these quantities the approach based on the solution of the Orr-Sommerfeld equation modified by a specific turbulent model was proposed. The most used model is shown by (Abrams, 1984). Although the dimensionless wave number α^* defined by (Abrams, 1984) is given in the range

$$0.0005 < \alpha *= \frac{2\pi\nu}{\lambda u *} < 0.01, \qquad (1)$$

where u^* is friction velocity, λ wavelength and ν kinematic viscosity, this model is validated only by experiments carried out for the selected ratio of wave amplitude to wavelength $a/\lambda = 0.007$. This fact, as well as the need to obtain data for models mentioned above, has motivated the validation of results and assumptions of this computational model for a larger number of ratios a/λ by a different methodology. Given the apparent complexity of real experiments, the approach of numerical experiments using CFD methods was chosen.

2. Characteristics of the CFD model

According to theoretical models based on the Kelvin-Helmholtz theory, the hydrodynamic instabilities grows at a speed of the gas flow around U = 7 m/s (Hanratty, 1983). Therefore, the external flow velocity was set in the range U = 2-12 m/s. The range of ratios a/λ is based on the assumption that the instability arises from infinitesimal deviations of the surface from equilibrium level. The geometry of the waves was therefore defined by the scope of the ratio a/λ ranging from 0.005 to 0.05 covering also the experimental setup by (Abrams, 1984). The geometric model was created in software StarCCM+. The waves were modeled by a harmonic function with constant amplitude a = 0.5 mm.

Due to the fact that the investigated physical parameters are affected by the growth of the boundary layer thickness, the computational domain was created in such a way that the area of measurement of physical quantities corresponds to the wave crest at the distance of 0.75 m from the leading edge. This

* Ing. Stanislav Knotek and prof. Ing. Miroslav Jícha, CSc.: Energy Institute, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, e-mails: knotek@fme.vutbr.cz, jicha@fme.vutbr.cz

geometrical configuration induces the same local Reynolds number Re_x for the same velocity of air flow, which allows the study of the influence of the ratio a/λ on the values of physical characteristics. Computational grid density was chosen so that, in the case of the shortest wavelength, the section of one wavelength in the direction of airflow is generated by 20 computational cells. Due to the influence of the velocity profile on the wall shear stress, 12 prismatic layers were created in the near-wall region to increase the accuracy of the model. Given the symmetrical nature of the problem, 2D geometry was used. The mesh in the case of the ratio a/λ = 0.025 is shown in Fig. 1.

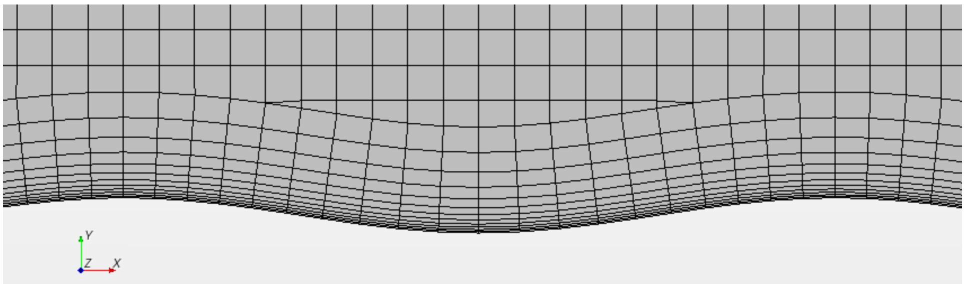

Fig. 1: The near-wall region mesh of the geometry model.

The height of the computational domain in all cases was set to h = 0.05 m. On the upper side, the symmetry boundary condition corresponding to the flow over the flat plate was prescribed. Because of the unknown velocity profile above the wavy surface, the uniform velocity profile was set on the input located on the left-hand side of the computational area. The boundary layer thickness was along the entire length of the area in all cases less than h/2. Given the geometric configuration and the nature of the flow over the surface, the turbulence model k-ω SST, see (Mentera, 1994), was chosen.

3. Theoretical background

The paper (Abrams, 1984) presents a theoretical model of flow over a wavy surface that is defined by harmonic function

$$y = a\cos\alpha x\,, \tag{2}$$

where α=2π/λ is wavenumber corresponding to the wavelength λ. The model is based on the solution of the linearized Navier-Stokes equation for parallel flow with implemented turbulence model. The basic assumption of the model is the condition that the amplitude of the wave was small in comparison with the wavelength and the thickness of the boundary layer. Under these assumptions, the pressure and shear stress acting on the surface in the direction of the basic flow (x-direction) can be expressed by relations

$$\tau = \overline{\tau} + \tau' = \overline{\tau} + a\hat{\tau}e^{i\alpha x}, \tag{3}$$

$$P = \overline{P} + P' = \overline{P} + a\hat{P}e^{i\alpha x}, \tag{4}$$

where $\hat{\tau}$ a $\hat{P}$ are complex numbers

$$\hat{\tau} = \tau_{SR} + i\tau_{SI}, \tag{5}$$

$$\hat{P} = P_{SR} + iP_{SI}\,. \tag{6}$$

The shear stress and pressure fluctuations are therefore modeled by harmonic functions and described by formulas

$$\tau' = a(\tau_{SR}\cos\alpha x - \tau_{SI}\sin\alpha x), \tag{7}$$

$$P' = a(P_{SR}\cos\alpha x - P_{SI}\sin\alpha x), \tag{8}$$

where quantities τ_{SR} , $\tau_{SI,}$ P_{SR} a P_{SI} are dependent on the air velocity and on the wavenumber α.

4. Results

4.1. Wall shear stress

From the formulas (3) and (7) follows that the wall shear stress fluctuation is modelled by harmonic function. The amplitude of this quantity and its phase shift against the wavy surface are defined by variables τ_{SR} and τ_{SI}. Simulations results, see Fig. 2, shows that the course of the average wall shear stress is harmonic for velocities lower than U = 12 m/s if $\lambda/a \geq 60$. However, for shorter wavelengths, the back-flow occurs, see Fig. 3, for all velocities greater than 2 m/s and therefore the harmonic character is deformed.

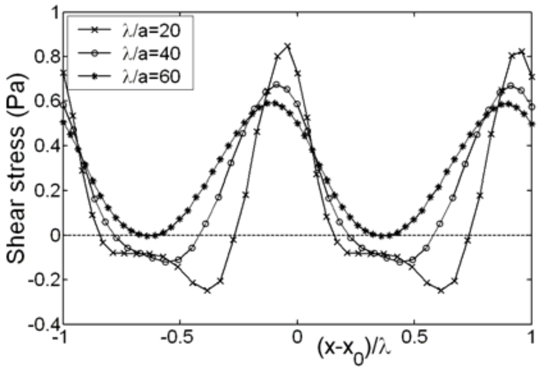

Fig. 2: The course of the shear stress for U=12 m/s and λ=[0.01;0.02;0.03]m.

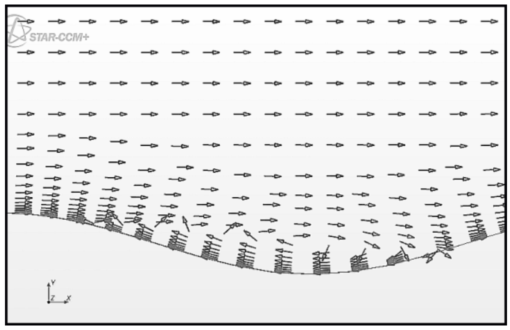

Fig. 3: Illustration of the back-flow for U=12 m/s and λ=0.01m .

Fig. 2 indicates that the wavelength λ affects the amplitude and phase shift of the wall shear stress maximum to the wave crest. Recall that x_0=0 in Fig. 2 corresponds to the wave crest at distance 0.75 m from the leading edge for all wavelengths. The dependency of the maximum values and phase shifts on the ratio λ/a shows Figs. 4 and 5 respectively.

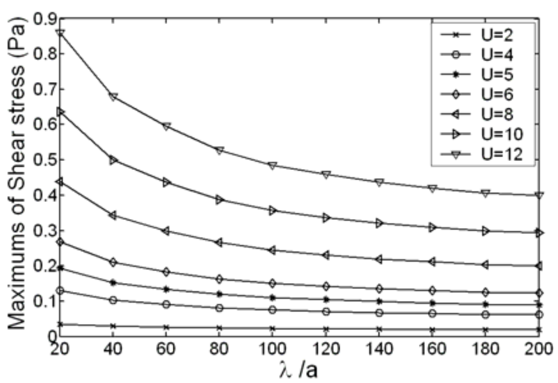

Fig. 4:Shear stress maximums in dependence on the ratio λ/a=20-200 for U=2-12 m/s.

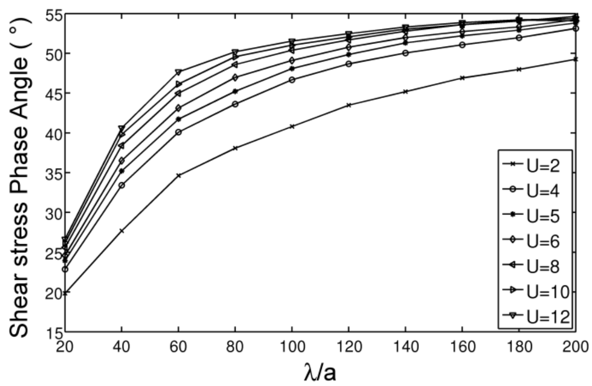

Fig. 5: Phase shift of the shear stress maximums in dependence on ratio λ/a for U=2-12 m/s.

Fig. 4 illustrates that, for different flow velocities, the curves of the wall shear stress reduction in dependence on the growing ratio λ/a are mutually correlated. In contrast, the phase shifts of the wall shear stress to the wave crest do not show such as degree of correlation for different flow velocities, see Fig. 4. However, a clear increasing trend with increasing ratio λ/a is observed. Note that 360° degree phase shift corresponds to the λ shift of the wall shear stress maximum against the wave crest in Fig. 5.

4.2. Pressure

As in the case of the wall shear stress, simulations show that the pressure profile can be considered as harmonic if $\lambda/a \geq 60$. Fig. 6 illustrates the dependence of pressure minimums which are located near the wave crests and are important for the liquid film instabilities as well as the maximum values of the shear stress. From the figure can be further seen that minimums of the curves are located between λ/a = 40 and λ/a = 60. From the simulations data does not follow a well-defined dependence of the wave crests vs. pressure minimums phase shifts on the ratio λ/a. However all values of the shifts of the pressure minimums lie in the range from 2° to 6° for external flow velocities greater than 2 m/s.

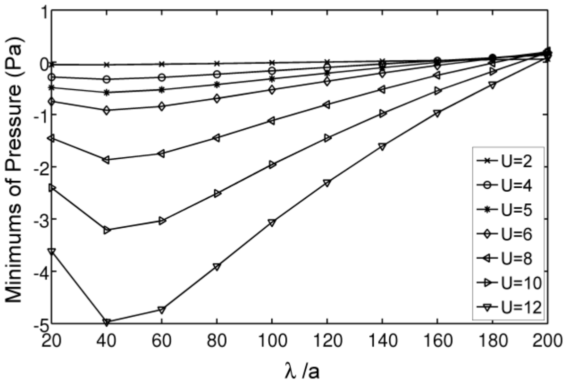

Fig. 6: The pressure minimums in dependence on λ/a for U=2-12 m/s.

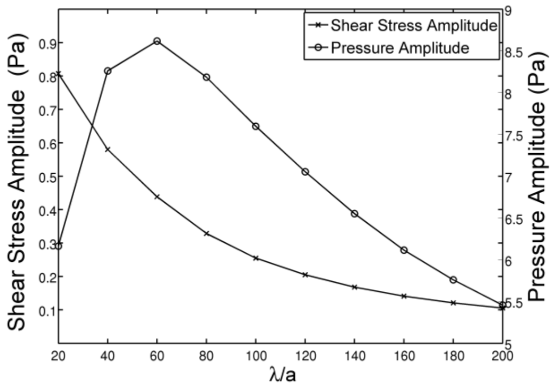

Fig. 7: The amplitudes of shear stress and pressure fluctuations for U=10 m/s.

In the solution of the liquid film instability problem, the amplitudes of fluctuations $|\tau'|$ and $|P'|$ have its significance as well as average values of these quantities. The simulations shows that the amplitude of $|\tau'|$ decreases with increasing λ/a, while the amplitude $|P'|$ reaches its maximum in the neighborhood of the ratio λ/a = 60. Fig. 7 illustrates these quantities for U=10 m/s.

5. Conclusions

This paper presents results of simulations of flow over a wavy solid surface described by a harmonic function and defined via the ratio of wavelength to the wave amplitude λ/a ranging from 20 to 200. The external flow velocity was set in the range from 2 to 12 m/s. With regard to the application of these results in the problem of the liquid film instability, the shear stress and pressure forces acting on the surface were studied. The aim of the research is primarily to assess the adequacy of computational models and their assumptions for selected geometrical and physical configuration. Subsequently, the issue is the possibility of using data obtained from CFD simulations as input parameters to the liquid film instability models.

The simulation results show that the assumptions of computational models are satisfied for λ/a≥60 at least for the external flow velocity up to 12 m/s. In general, simulations confirm a considerable dependence of the physical quantities on the ratio λ/a. However, the computed values of friction velocity induce values of α^* ranging from 0.0017 to 0.0574, which insufficiently cover the interval (1). Therefore, further simulations for greater external velocities are needed to detailed examination of the obtained data in comparison with computational models.

Acknowledgement

The article was supported by the project of Czech Science Foundation GA101/08/0096.

References

Abrams, J. (1984) Turbulent flow over small amplitude solid waves, Ph.D. Dissertation, University of Illinois at Urbana-Champaign.

Hanratty, T. J. (1983) Interfacial instabilities caused by air flow over a thin liquid layers, Waves on Fluid Interfaces (Edited by Meyer, R. E.), Academic Press, New York, pp. 221-259.

Menter, F. R. (1994) Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications, AIAA Journal, vol. 32, pp. 269-289.